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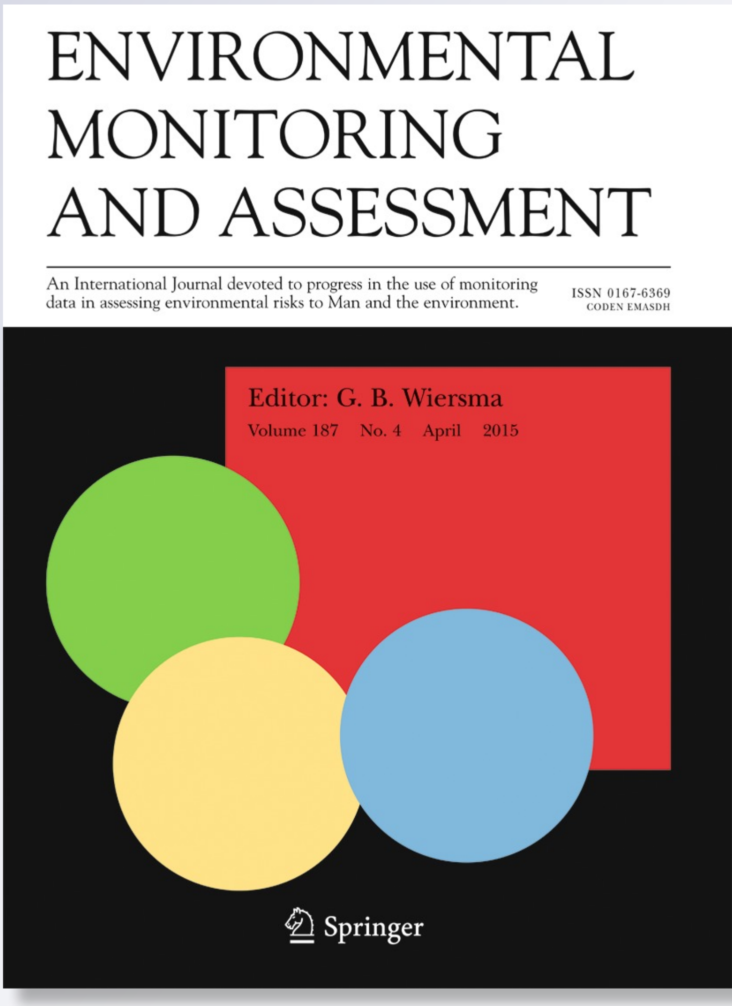

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Characteristics of a cyclonic eddy and its influence on mesozooplankton community in the northern Bay of Bengal during early winter monsoon

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Abstract Characteristics of a cold-core eddy and its influence on the mesozooplankton community were studied along the central (87° E) Bay of Bengal during winter monsoon (November 2008) based on in situ data. The thermo-haline structure and the satellite-derived sea level anomaly maps showed the presence of a cyclonic eddy between 16° N and 20° N. The nutrient enhancement due to the eddy pumping in the euphotic column (~50 m) had resulted in high chlorophyll *a* concentration, a factor of 8 times higher than that outside the eddy, which led to higher mesozooplankton biovolume (0.35 ±0.36 ml m^{-3}) and abundance (276±184 ind m^{-3}). The northern cyclonic eddy (NCE) seems to exist for approximately 6 months between July and January. During summer, the NCE is forced by local wind stress curl and the resultant Ekman pumping, whereas during fall and early phase of the winter, it is sustained by westward propagating semi-annual Rossby waves. The longer existence of NCE in the study region, which originated 6 months prior to the present observation, provides a favourable environment for the mesozooplankton community to grow and reproduce, resulting in noticeable increase in the biovolume. Hence, the persistent and longer existence of NCE significantly influences the biological production of the generally oligotrophic BoB, making it locally biologically *'active'*.

Keywords Cyclonic eddy · Wind stress curl · Rossby waves · Nutrients · Chlorophyll · Zooplankton · Winter monsoon · Bay of Bengal

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Introduction

The Bay of Bengal (BoB) is a semi-enclosed tropical basin situated in the eastern part of the Indian Ocean. The BoB is under the influence of seasonally reversing monsoon winds, which are southwesterly during the summer (June–September) and northeasterly during the winter (November–February), and is impacted remotely by the zonal winds from the equatorial Indian Ocean (McCreary et al. 1993). In addition, the BoB receives large quantities of fresh water both from rainfall and river runoff, and here, the precipitation exceeds evaporation (Prasad 1997; Rao and Sivakumar 2003). The major rivers such as Ganges, Brahmaputra, Godavari and Irawaddy discharge about 1.5×10^{12} m^3 of fresh water into the BoB (UNESCO 1988) while the suspended sediment associated with the river discharge is estimated to be 1.38×10^9 ton $year^{-1}$ (Subramanian 1993). The excess precipitation and large river runoff considerably reduce the salinity in the upper layers of

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the basin, particularly in the northern region (Nuncio and Prasanna Kumar 2012).

Generally, the BoB is considered to sustain low biological production (Qasim 1977; Madhu et al. 2002). The suggested possible reasons for the low production are cloud cover, large sediment load, narrow shelf, stable stratification and weak winter cooling (Qasim 1977; Sengupta et al. 1977; Radhakrishna et al. 1978; Gomes et al. 2000; Madhupratap et al. 2003; Jyothibabu et al. 2004). However, episodic events such as cyclones (Madhu et al. 2002; Vinayachandran and Mathew 2003; Maneesha et al. 2011; Jyothibabu et al. 2015) and mesoscale features like cyclonic eddy, ranging in kilometres and persistent for days to months, are capable of enhancing the biological production of the oligotrophic BoB, by introducing nutrients from subsurface waters to the surface. Observations on eddies from different parts of the world oceans have also reported enhanced biological production in response to such mesoscale features (Falkowski et al. 1991; Allen et al. 1996; McGillicuddy et al. 1998; McNeil et al. 1999; Robinson et al. 1993; Aristegui et al. 1997; Letelier et al. 2000; Moran et al. 2001; Barth et al. 2001; Garcia et al. 2004). Several studies have documented the existence of eddies in the BoB during different seasons (Ramasastry and Balaramamurty 1957; Rao and Sastry 1981; Legeckis 1987; Babu et al. 1991, 2003; Murty et al. 1993, 2000; Shetye et al. 1993; Sanilkumar et al. 1997; Madhusoodhanan and James 2003; Prasanna Kumar et al. 2002, 2007; Muraleedharan et al. 2007; Kurien et al. 2010; Nuncio and Prasanna Kumar 2012). Recently, Jyothibabu et al. (2015) have studied the phytoplankton size structure of the cyclonic/anticyclonic eddies developed as meanders of Summer Monsoon Current (SMC) in the southern BoB.

However, detailed observations explaining the physical, chemical and biological attributes associated with eddies are few. The majority of the observations on eddy and its implications are limited to measurements of the primary producers; studies explaining the mesozooplankton community structure are very few. Murty et al. (2000) demonstrated the effect of vertical stability and mesoscale circulation patterns on the spatial distribution of deep chlorophyll maximum (DCM) and its concentration in the BoB. Recently, Prasanna Kumar et al. (2010) have reported the influence of cyclonic eddies on sustaining moderate amount of chlorophyll biomass and productivity almost throughout the year. The cyclonic eddies have also been reported to sustain high mesozooplankton standing stock (biomass, abundance and diversity) in the BoB (Muraleedharan et al. 2007). Veronica (2008) has reported that such episodic events enhance the production of BoB to the extent which is comparable with that of the Arabian Sea.

Nuncio (2007) analysed the characteristics of the cyclonic eddies in the central BoB at 88° E and along the western shelf and suggested that baroclinic instability is the key mechanism controlling their formation. However, details on the formation and propagation mechanisms of the eddies, their frequency of occurrence and life span (developing, maturing and collapsing stages) in the BoB are crucial to assess their relative importance on the biogeochemical processes of this bay ecosystem. Understanding of how the mesoscale eddies may affect the mesozooplankton biomass and community structure will enhance our perception of carbon cycling and sequestration, in the BoB, which is considered to be an oligotrophic environment where the total biological production is relatively low. In this study, we provide in situ hydrographic evidences describing the dimension and spatial extent of a long-lived large cyclonic eddy in the northern BoB during early winter of 2008 and its impact on biological production in terms of mesozooplankton biovolume and composition.

Materials and methods

Observations were made on board FORV *Sagar Sampada* (SS-259 cruise), between 5° 48′ N and 21° N along 87° E in the BoB during the winter monsoon (19^{th} to 30^{th} November) of 2008, from eight stations, spaced approximately at a distance of 2° between the stations (Fig. 1). Surface meteorological parameters (wind speed, wind direction, air temperature and atmospheric pressure) were measured using shipboard automated data acquisition system. A Sea-Bird CTD (conductivity-temperature-depth) 911 *plus* was operated to obtain the vertical profiles of temperature (accuracy ±0.001 °C) and salinity (conductivity ±0.0001) in the upper 1000 m water column with a bin size of 1 m. These data were subjected to quality check by Sea-Bird data processing software. CTD salinity data were calibrated against water collected simultaneously and analysed onboard using a Guildline 8400 Autosal. The skin layer temperature was measured using a bucket thermometer (accuracy ±0.1 °C) at each station. In the present study, the mixed layer depth (MLD) was taken

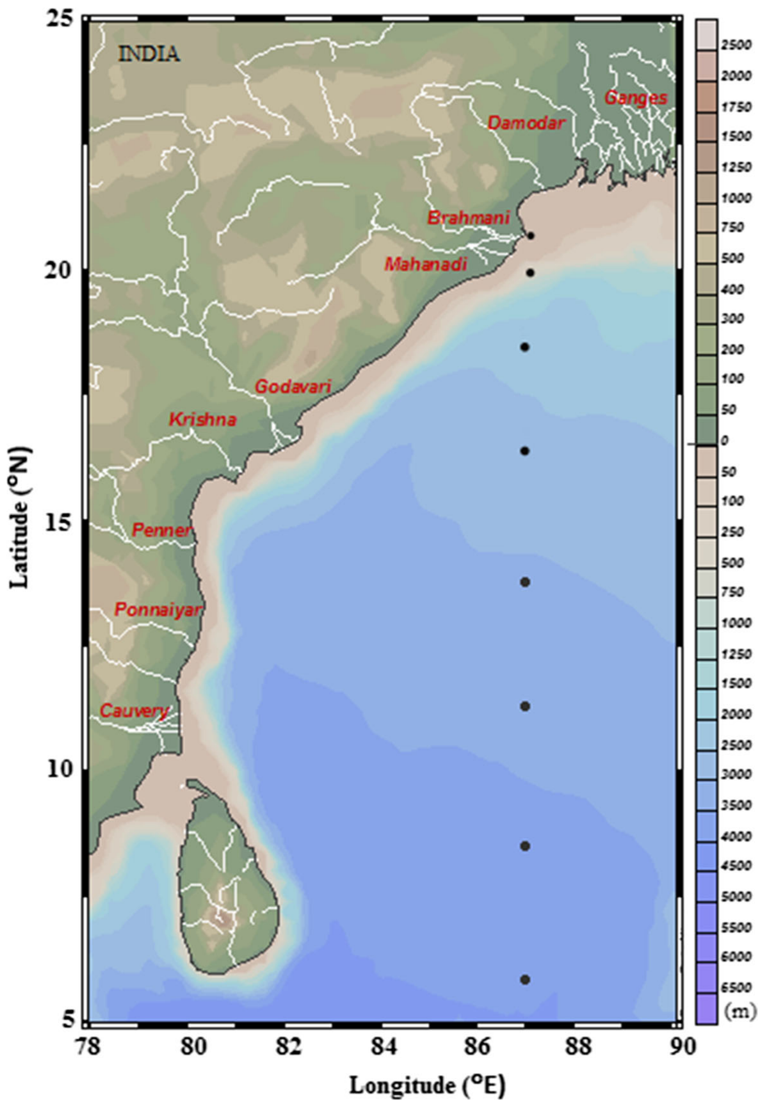


Fig. 1 Central Bay of Bengal, showing the hydrographic and biological stations on the bathymetric chart. *Black dots* represent the station locations during the study period. During the cruise, observations were made from the southern side to northern side of the Bay of Bengal

as the depth at which the density (∂σ/∂z) increased by 0.2 kg m^{-3} from its surface value (Shetye et al. 1996; Sabu and Revichandran 2011). The thermocline is the transition layer between the mixed layer and the deep water. In the present study, the depth of 15 °C isotherm was considered as the representative depth of bottom of thermocline (Madhupratap et al. 2003).

Water samples were collected from seven discrete depths (surface, 10, 20, 50, 75, 100 and 120 m) using Niskin samplers attached to CTD rosette. SKALAR Autoanalyser (Model SA-1050) installed onboard was used to estimate the dissolved nutrients (nitrite, nitrate, phosphate and silicate) following standard procedures (Grasshoff et al. 1983). For chlorophyll *a* (Chl *a*) estimation, 2 L of sea water was filtered through Whatman GF/F filter (47 mm). The photosynthetic pigments retained on the filters were extracted in 90 % acetone and estimated spectrophotometrically (Strickland and Parsons 1972). Column values of Chl *a* were calculated by integrating discrete depth values from surface to 120 m. The mesozooplankton samples within MLD and thermocline depth were collected with a Multiple Plankton Net (HydroBios, mesh size 200 μm, mouth area 0.25 m^2), and the biovolume was estimated by displacement volume method.

In addition to the 'in situ' data, we also used satellite SST from TRMM/TMI (1/4°×1/4°, www.ssmi.com), Quikscatteraometer (QuickSCAT, www.ssmi.com) winds (1/2°×1/2°) and merged sea-surface height anomalies (SSHA, 1/3°×1/3°) of Topex-Posiedon/ERS 1/2/Jason1 (www.aviso.oceanobs.com). From SSHA's, the residual sea-surface geostrophic velocity components (U′ and V′) were computed. We also used the monthly composite wind vector (scalar wind speed with corresponding *u* and *v* component) from the QuikSCAT to compute the curl of the wind. The wind stress was then calculated using a constant drag coefficient (1.2×10^{-3}) and air density (1.3 kg m^{-3}). Ekman pumping was calculated using the equation,

$$w_e = {}^{\mathrm{Curl}(\tau)}/_{\rho f} \quad (1)$$

where τ is the surface wind stress, ρ is the density of sea water and f is the coriolis parameter. Theoretical phase speed of the Rossby wave was computed using the equation (Gill 1982; Jury and Huang 2004),

$$C = {}^{-\beta g' H}/_{f2} \quad (2)$$

where β is the meridional gradient of f, g′ is the reduced gravity and H is the thermocline depth with values assumed to be $\beta=2.21\times10^{-11}$, $g'=0.02$, $f_2=1.8\times10^{-11}$ and $H=150$ m for 17° N (observation). Monthly composite ocean colour imageries (4-km resolution) from MODerate resolution Imaging Spectrometer (MODIS) (http://oceancolor.gsfc.nasa.gov/cgi/l3) were also analysed to understand the Chl *a* distribution in the eddy region. Euphotic depth (Z_{eu}) was computed from the MODIS data (Morel and Berthon 1989) using the expression,

$$\begin{aligned} Z_{eu} &= 568.2(C_{tot})^{-0.746} \text{ for Zeu} < 102 \text{ and} \\ Z_{eu} &= 568.2\,(C_{tot})^{-0.293} \text{ for Zeu} > 102 \end{aligned} \quad (3)$$

C_{tot} is the total pigment content within the euphotic layer depth (0 to Zeu).

Results

Physical parameters

The atmospheric conditions that prevailed in the BoB during the present study represent the general characteristic feature of the winter monsoon. The average wind speed along 87° E (5° to 20° N) was 8 m s^{-1}, and north of 20° N weak winds (2.5 m s^{-1}) prevailed (Fig. 2a). Wind direction was predominantly easterly between 6° and 11° N and north of 11° N it was northeasterly (Fig. 2b). The distribution of winds from the satellite during the study period correlated well with the observed data (figure not shown). Air temperature showed a gradual decrease from 29 °C in the south to 24.8 °C in the north and the diurnal variation was ~1 °C (Fig. 2c). In contrast to air temperature, the atmospheric pressure showed a clear semi-diurnal variation with a steady increase towards the north from 1005 mb at 5° 45′ N to 1015 mb at 20° 30′ N (Fig. 2d).

Vertical distribution of water temperature along 87° E showed warm (>29 °C) and thick isothermal layer (~50 m) south of 10° N. However, with increasing latitudes, the temperature in the isothermal layer showed a gradual decrease and was about 1.5 °C colder than in the south (Fig. 3a). Satellite-based SST distribution also showed prominent variation between south (~29.2 °C) and north (~28.2 °C) (figure not shown). The most important feature in the thermal structure was the doming of isotherms centred between 16° and 20° N which was more prominent in the subsurface layers (<40 m). The 25 °C isotherm in the doming region shifted from a depth of 90 m at 14° N to 50 m at 18° N, showing a vertical displacement of 40 m. The maximum vertical displacement of the 25 °C isotherm at 18° N indicates the approximate position of the centre of the doming. The intensity of the doming decreased with depth, and below 300 m the undulations in the isotherms were not evident (not shown).

In the BoB, the variations of temperature and salinity are not uniform particularly in the north due to river runoff and precipitation during the summer. Hence, the criteria for defining the MLD were based on density variation rather than temperature or salinity. In general, the mixed layer depth was shallow, especially in the south. The mixed layer was 17 m at 5° 48′ N, which gradually increased to 48 m at 16° N and then sharply decreased to 31 m at 18° N. Further north at 20° N, it deepened to 47 m and again shoaled to 16 m at 21° N (Fig. 3a). The doming feature observed in the region between 16° and 20° N decreased the mixed layer by about 18 m at the centre of the doming (18° N).

The vertical distribution of salinity showed the presence of low saline water (29–32.4) in the upper 30 m between 18° and 21° N. As a result, salinity distribution showed strong vertical and horizontal gradients in this region (Fig. 3b). The low saline water observed in the north may be due to the fresh water discharge from the

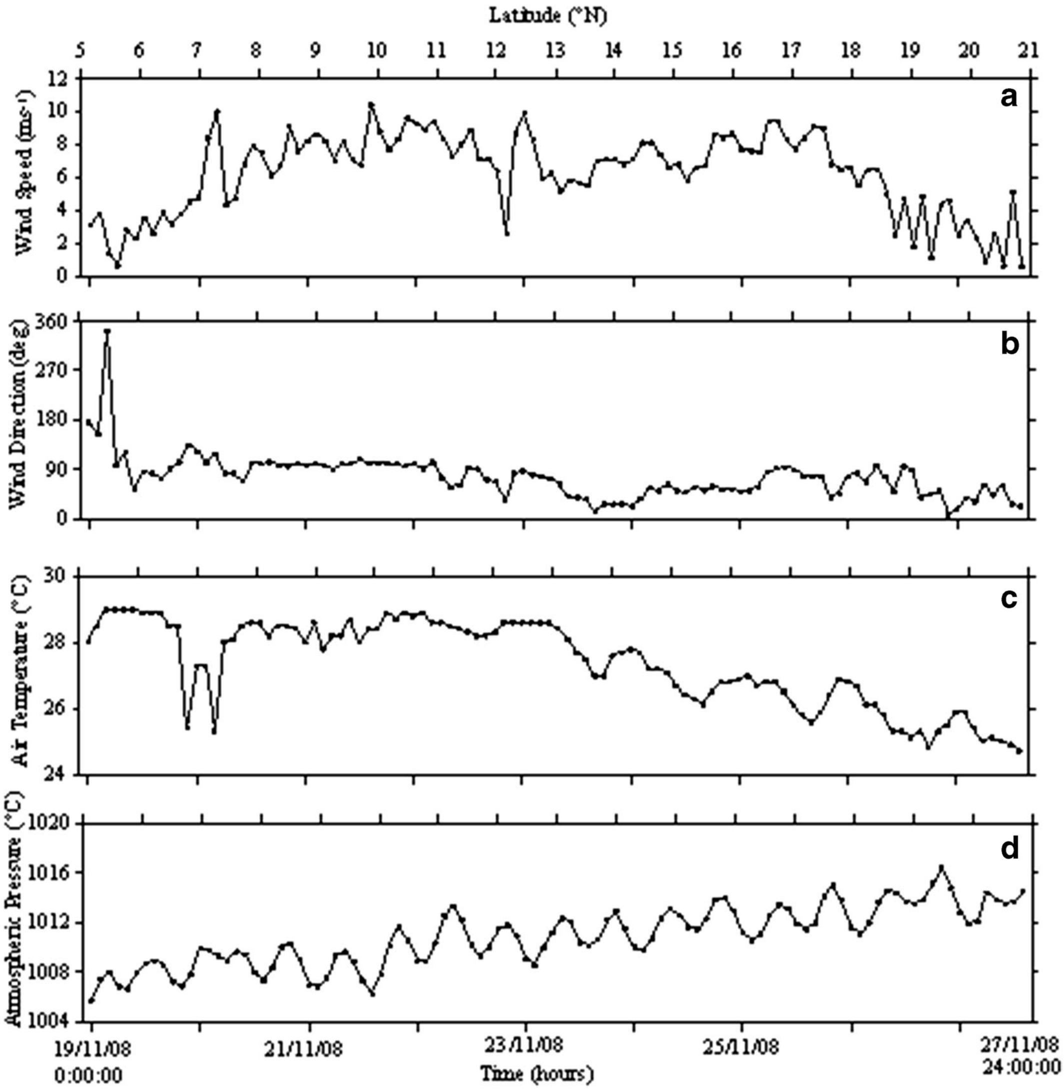


Fig. 2 Latitudinal variation of **a** wind speed (ms^{-1}), **b** wind direction (deg), **c** air temperature (°C) and **d** atmospheric pressure (mbar) from 19th to 30th November 2008. *Black dots* represent observation points

river Ganges. The surface salinity was at its maximum of 33.6 from the southernmost station (5° 48′ N) to 15° N. Also, the salinity between 100- and 300-m columns was found to be spatially uniform (figure not shown). Consistent with the thermal structure, the isohalines also showed doming and this was visible below 30-m depth, centred between 16° and 20° N. The doming of isohalines at 18° N increased the salinity at 50-m depth by 0.4 and the 33.6 contour was pushed down to about 50-m depth in the centre of the depression. The density distribution also showed the doming feature between 18° and 20° N, coinciding with the distribution pattern of temperature and salinity (Fig. 3c).

Chemical parameters

Corresponding with the thermo-haline oscillations, the vertical distribution of dissolved oxygen (DO) also showed fluctuations below 40-m depth, between 16° and 20° N. The 2 ml L^{-1} DO contour shoaled from a depth of about 100 m at 14° N to 50–60 m at the centre of doming (18° N), showing a vertical displacement of 40 to 50 m (Fig. 3d). Also, a sharp decrease of DO from 4.8 ml L^{-1} at 40 m to 0.8 ml L^{-1} at 65 m was observed in the doming region. The nitrate concentration in the upper 35-m water column was at an undetectable level except at the centre of the doming whereas it was

0.1 μM. However, some fluctuations in nutricline were clearly seen (Fig. 3e). The doming at 18° N had resulted in appreciable enhancement of nitrate in the euphotic column (~50 m). The 2-μM isopleths located at 55-m depth at 13° N shoaled to about 30 m further towards north. The phosphate concentration in the upper 40 m was also at an undetectable level, but showed doming features at deeper depths between 16° and 20° N (Fig. 3f). The vertical distribution of silicate, like nitrate, showed increasing concentration with depth. The stations north of 16° N recorded higher values of surface silicate with maximum (10 μM) at 21° N (Fig. 3g), which was due to the riverine discharge as is evident from the salinity distribution. The doming features were also more pronounced in the silicate distribution between 16° and 20° N. Hence, consistent with the thermo-haline doming, the vertical distribution of nutrients also showed prominent oscillation in the upper water column.

Biological parameters

Chlorophyll a

The vertical distribution of Chl *a* (Fig. 3h) was consistent with that of the thermo-haline and nutrient structures. Chl *a* concentration in the surface varied and was higher (0.21±0.02 mg m^{-3}) in the doming region (between 16° and 20° N) compared to the region between 8° N and 14° N (0.01±0.001 mg m^{-3}) (Fig. 3i). In agreement with the in situ observations, the Chl *a* derived from the satellite imageries (MODIS Aqua) along 87° E also showed a higher concentration (>0.5 mg m^{-3}) between 16° and 20° N during October–November 2008 (Fig. 4a, b). The column-integrated Chl *a* (upper 120 m) also showed a similar pattern, with low concentration (3±0.8 mg m^{-2}) between 8° N and 14° N (Fig. 5a). North of 14° N, the areal chlorophyll concentration was exceptionally high (25.7±3.6 mg m^{-2}), and the maximum (29.4 mg m^{-2}) was observed at 18° 45′ N. The DCM was located at about 75-m depth in the south (13° 46′ N) and shoaled to 45 m in the north (18° 45′ N), with a concentration as high as 0.4 mg m^{-3}.

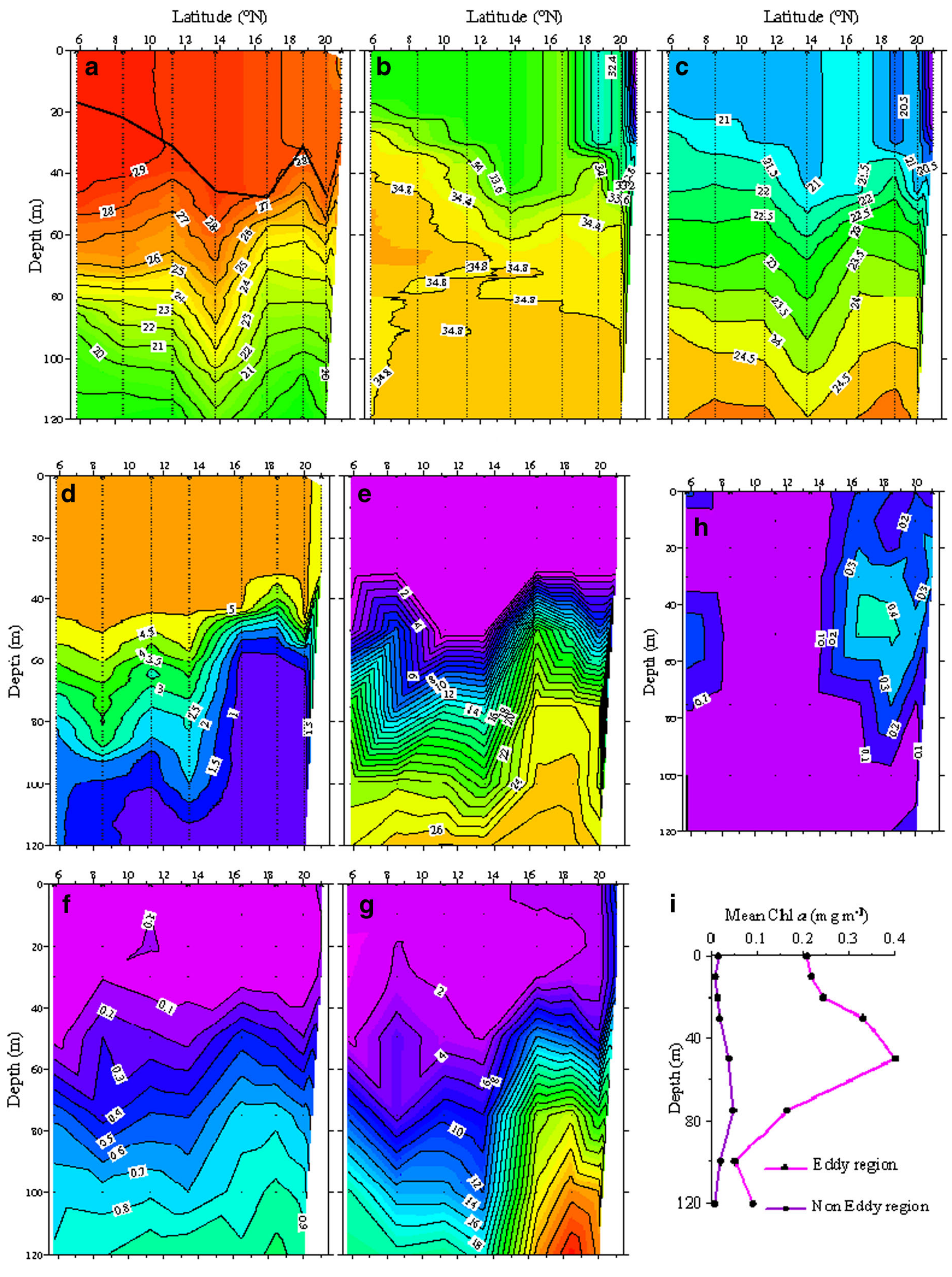
Mesozooplankton biovolume and composition

The mesozooplankton biovolume and abundance in the mixed layer of the doming region (16°–20° N) was considerably high (av. 0.35±0.36 ml m^{-3}) compared to that at 13° 46′ N (0.09 ml m^{-3}). However, the thermocline layer in the doming region sustained low biovolume (av. 0.09±0.05 ml m^{-3}) than the mixed layer (Fig. 5b). Correspondingly, the numerical abundance was also higher in the mixed layer (av. 277±184 ind m^{-3}) than in the thermocline layer (av. 114±94 ind m^{-3}) and also outside the doming region (av. for mixed layer 128±91 ind m^{-3}, av. for thermocline layer 71±14 ind m^{-3}). It was also observed that the biovolume as well as the numerical abundance in the mixed layer was high (0.77 ml m^{-3} and 472 ind m^{-3}, respectively) at the northern side (20° N) of the doming than at the centre (18° N; 0.19 ml m^{-3} and 105 ind m^{-3}, respectively). On the other hand, a reverse trend was observed in the thermocline layer where high mesozooplankton standing stock was observed in the centre of the doming region (biovolume 0.14 ml m^{-3}, numerical abundance 223 ind m^{-3}) than the northern region (0.10 ml m^{-3}; 59 ind m^{-3}).

Among the major mesozooplankton taxa, Copepoda dominated in the mixed layer of the doming region (av. 225±144 ind m^{-3}), contributing to 81 % of the total abundance in the doming region (16°–20° N). However, the maximum abundance of this taxon was observed in the northern periphery of the doming region (371 ind m^{-3}), coinciding with the maximum biovolume. On the other hand, in thermocline layer, though the numerical abundance of Copepoda was considerably low (av. 106±91 ind m^{-3}), its contribution accounted for 94 % (211 ind m^{-3}) of the total abundance in the centre of the doming. Outside the doming region, its abundance was considerably low and also differed between the mixed layer (45 ind m^{-3}) and the thermocline layer (75 ind m^{-3}).

The contribution of non-copepod taxa in the doming region, on average, was 51 ind m^{-3}, showing significant variations between the mixed and thermocline layers (Table 1). In the mixed layer, Appendicularia was the second abundant group, having maximum abundance in the northern side of the doming (35 ind m^{-3}), followed by Chaetognatha (20 ind m^{-3}), Amphipoda (7 ind m^{-3}) and Euphausiacea (4 ind m^{-3}). Ostracoda occurred in

Fig. 3 Vertical distribution of temperature, salinity, density, dissolved oxygen (mL L^{-1}), nitrate (μm), phosphate (μm), silicate (μm) and Chl *a* along 87° E during the study period and mean distribution of Chl *a* in the NCE region and non-eddy region. *Black dots* represent sampling points. *Black continuous line* in **a** represents MLD ▶


Latitude (°N)
Latitude (°N)
Latitude (°N)
Depth (m)
a
b
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Mean Chl a (mg m⁻³)
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Eddy region
Non Eddy region

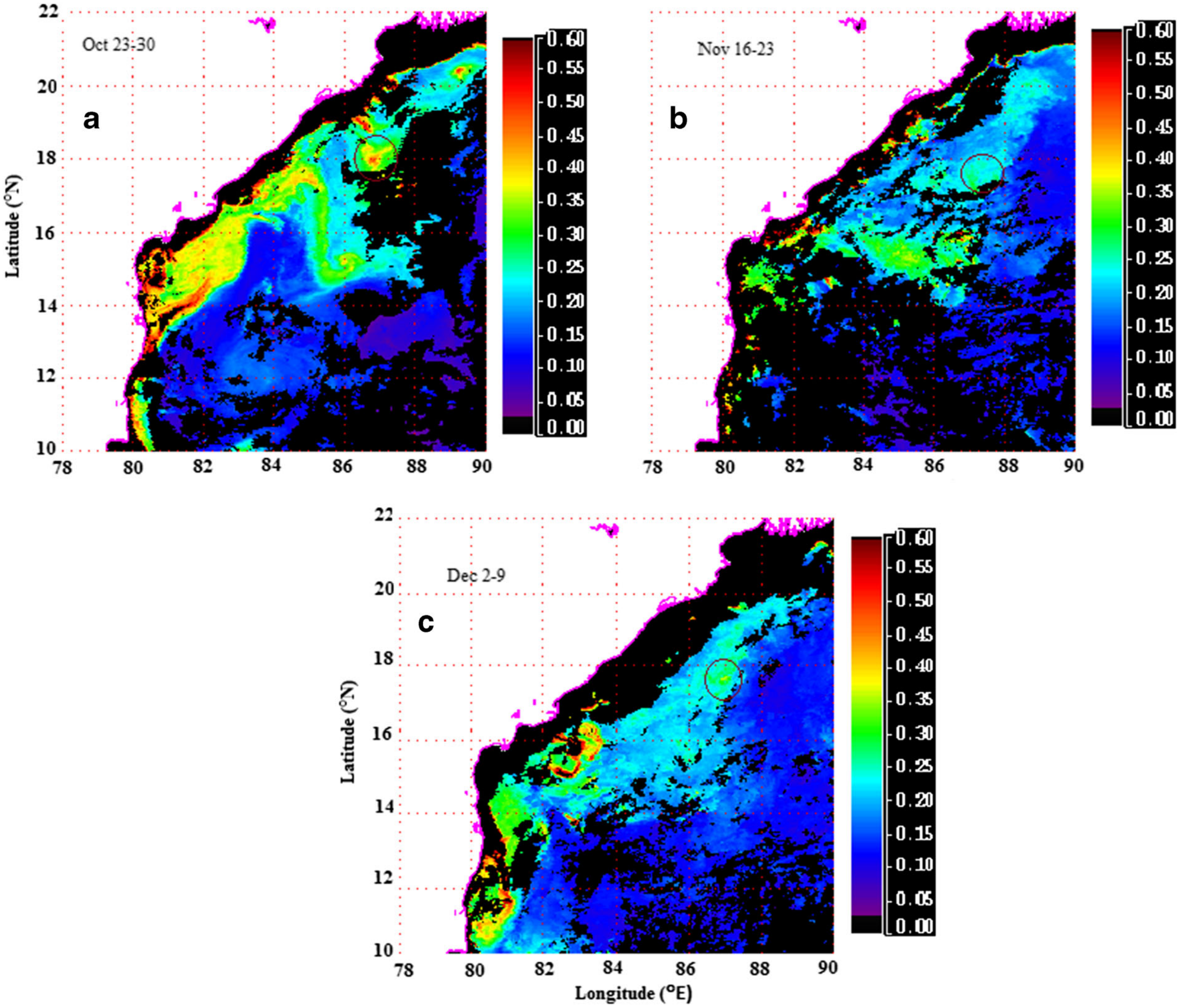


Fig. 4 Distribution of monthly mean Chl *a* (mg m^{-3}) in the BoB during **a** October, **b** November and **c** December 2008. *Red circle* represents the NCE region

considerable numbers only in the centre of the doming, both in the mixed and thermocline layers (10 and 5 ind m^{-3}, respectively). However, gelatinous groups such as Medusa (12 ind m^{-3}), Siphonophora (7 ind m^{-3}) and Salpa (3 ind m^{-3}) occurred in fairly good numbers only in the mixed layer at 20° N.

Discussion

Formation and sustenance of cyclonic eddy

The doming feature observed in the thermo-haline structure between 16° and 20° N strongly suggests the presence of a physically mature cyclonic eddy in the study region. The presence of the cyclonic eddy (referred to hereafter as the NCE) was further confirmed by considering the 7-day average SSHA along with geostrophic currents during the study period. The NCE, centred at 18° N and 86° E, was found embedded in a large cyclonic circulation between 85° and 89° E and 16° and 20° N belt (Fig. 6a). It was approximately 300 km in diameter, depressed the sea level by about 20–25 cm and rotating with a speed of about 50–70 cm s^{-1}. The most distinct feature of the NCE was its longer life span, approximately 6 months (Fig. 6b), which developed in July (summer), grew in size and intensity in the subsequent months and dissipated in January (winter). This clearly indicates that the NCE

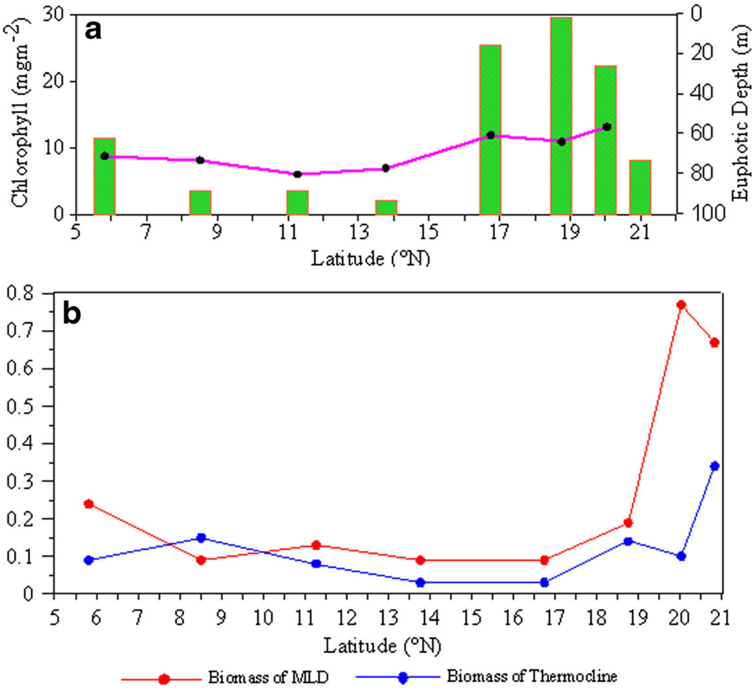


Fig. 5 Latitudinal variation of **a** column chlorophyll (mg m^{-2}) and **b** mesozooplankton biomass within MLD and thermocline in the Bay of Bengal during the study period (19th to 30th November 2008). *Purple line* represents the euphotic depth

during the study period was approximately 4 months old. Similar long-lived eddies (2 to 5 months) have been reported earlier from the southern BoB during the spring inter-monsoon in 2003 (Prasanna Kumar et al. 2007; Nuncio and Prasanna Kumar 2012). Hovmöller diagrams of SSHA along 87° E for the years 2005–2009 from January to December suggest that a NCE spins up regularly in the northern BoB. Also it is evident that the NCE is an annual recurring feature within the latitudinal belt of 16°–20° N during early winter

Table 1 Composition of mesozooplankton groups (in percentage) in the mixed layer depth and the thermocline layer

Groups	Mixed layer (ind m^{-3})				Thermocline layer (ind m^{-3})			
	13° 46′ N (outside the doming region)	16° 45′ N (Doming region)	18° 45′ N	20° N	13° 46′ N (outside the doming region)	16° 45′ N (Doming region)	18° 45′ N	20° N
Copepoda	45	222	83	372	75	52	211	55
Chaetognatha	6	7	7	20	2	3	3	2
Ostracoda	0	0.08	10	0	1.4	0.37	5	0
Decapoda	1.4	0.42	0.25	0.17	0.14	0.25	0.29	0.02
Amphipoda	1.21	0.25	0.51	7.5	0.31	0.03	0.40	0.18
Euphausiacea	1.30	4.8	1.8	4.08	0.46	0.75	0.29	0.68
Appendicularia	2.3	5.62	0	35.5	0.34	0.5	1.1	0
Polychaeta	2.7	0.42	0.64	4.6	0.32	0.62	0.23	0.72
Medusa	0.69	1.62	0	12	0	0.22	0.58	0.42
Siphonophora	1.4	3.06	0.77	7.14	0.32	0.97	0.52	0.15
Salpa	1.04	0	0	3.06	0.43	0	0	0
Fish larvae	0	0	0.39	1.5	0.02	0	0.14	0.08
Fish eggs	0	0	0	0.51	0.28	0.06	0	0
Foraminifera	0	7.6	0	0	0	1.5	0	0

(Fig. 6c). The NCE is forced twice annually, initially in July–September and later in October-November as depicted from the strong signals along the study area (87° E, Fig. 6c). The duration of existence (~6 months) of NCE during 2007 and 2008 (Fig. 6c) suggests that NCE sustains in the area for a longer period.

Three forcing mechanisms appear to be responsible for the eddy generation in this area, which are (i) the interaction of the large-scale currents with the bottom topography, (ii) local baroclinic instability and wind forcing, and (iii) coastally trapped Kelvin waves along the periphery of the BoB and westward propagating Rossby waves (Nuncio and Prasanna Kumar 2012). A closer examination of the bathymetry using ETOPO data (5-m resolution) and the location of the NCE ruled out the possibility of bottom topographic changes for triggering the NCE (Babu et al. 1991; Nuncio 2007). Therefore, we analysed the relative importance of the other two mechanisms for triggering the NCE and sustaining its existence.

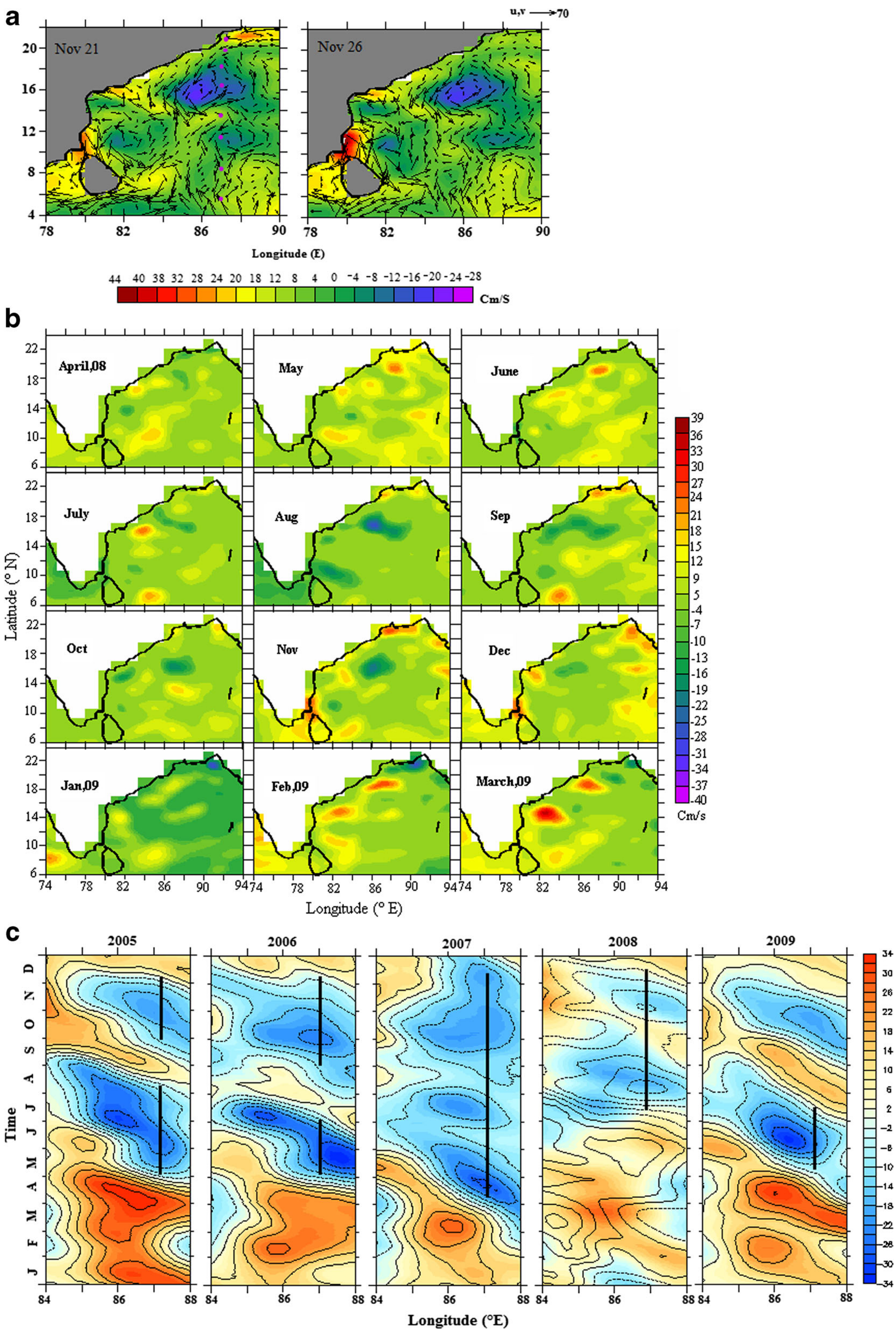
It is well known that the local wind stress plays an important role in driving the Ekman pumping and associated divergence in the near-surface layers leading to the uplifting of isotherms in the thermocline layer. To check whether the NCE and the large patch of low SSHA were forced by local wind stress, we examined the wind stress curl and the resultant Ekman pumping velocity (W_e) in the region (averaged between 86° E and 88° E) during 2008. The comparatively strong positive wind stress curl (4×10^{-7} Nm^{-3}) observed between 17° and 19° N was found to coincide spatially with the low SSHA. The curl-induced strong Ekman pumping (7×10^{-3} cm s^{-1}), producing divergence in the upper water column, which was balanced by the localized upwelling and eventually led to the formation of NCE during July–September (Fig. 7a, b).

In order to confirm this, we analysed the wind stress curl (i.e. a proxy for the Ekman pumping) in the NCE region (16–20° N and 86–88° E) from January to December for the years 2005–2009. The observed positive wind stress curl and Ekman pumping (June to September) during all the analysed years (Fig. 7c) showed a similar pattern in the NCE region, suggesting that the local wind stress curl in terms of Ekman pumping was the dominant driving force behind the formation of NCE during summer. However, the longer existence of the NCE during 2007 and 2008 and comparatively shorter existence (June to July) during 2005, 2006 and 2009

Fig. 6 a Snapshots of SSHA in the BoB during 21st and 26th November 2008 (*black dot* in the figure represents in situ locations). **b** Monthly variation of SSHA from April 2008 to March 2009 and **c** monthly mean SSHA variation along 87° E during 2005–2009 from January to December (*horizontal black line* represents the existence period of NCE along our study area) ▶

(marked with red line in Fig. 6b) suggest that the interannual variability of the wind forcing and the wind stress curl (Fig. 8) significantly influenced the forcing of the NCE in the BoB during summer (July–September). On contrary, during October–December, the wind stress curl was negative in the NCE region, indicating that the influence of wind stress curl beyond summer was weak. Therefore, we examined the role of the third forcing mechanism, i.e. Rossby waves for sustenance of NCE beyond summer.

In order to understand the signature of the most energetic semi-annual propagating Rossby waves in the study region, we filtered the 180-day oscillation in the SSHA using a low pass filter. The time-longitude plot of 180-day signal of SSHA along 17° N is shown in Fig. 9a. The Hovmuller diagram of the low frequency part clearly shows a continuous westward propagation of a low SSHA signal along 17° N. This implies the existence of the westward propagating semi-annual Rossby waves in the study region. The signatures of westward propagation of low SSHA was evident in other years as well (e.g. Fig. 9b). These propagations extended from around 92° E of the BoB up to the study region (87° E). The westward propagating signal at 17° N took about 120 days (August to November) to travel from 92° E to the study area, which implies a speed of 0.042 m s^{-1}. The theoretical baroclinic semi-annual Rossby wave phase speed at 17° N calculated using the expression given by Jury and Huang (2004) is 0.041 m s^{-1}. The estimated Rossby wave speed is in agreement with that expected from the theory (Gill 1982). The 180-day signal of SSHA along 18° N also showed the same signal, confirming the presence of Rossby wave signal in the NCE region. Thus, the eddy observed during the early winter may be associated with the westward propagating semi-annual Rossby waves in the northern BoB. These waves appear to originate from an equatorial Kelvin wave excited by the summer southwest monsoon wind (Yu et al. 1991). The energy imparted by these winds propagate as Kelvin waves and further propagate along the eastern rim of the BoB as coastal Kelvin waves and subsequently radiate westward as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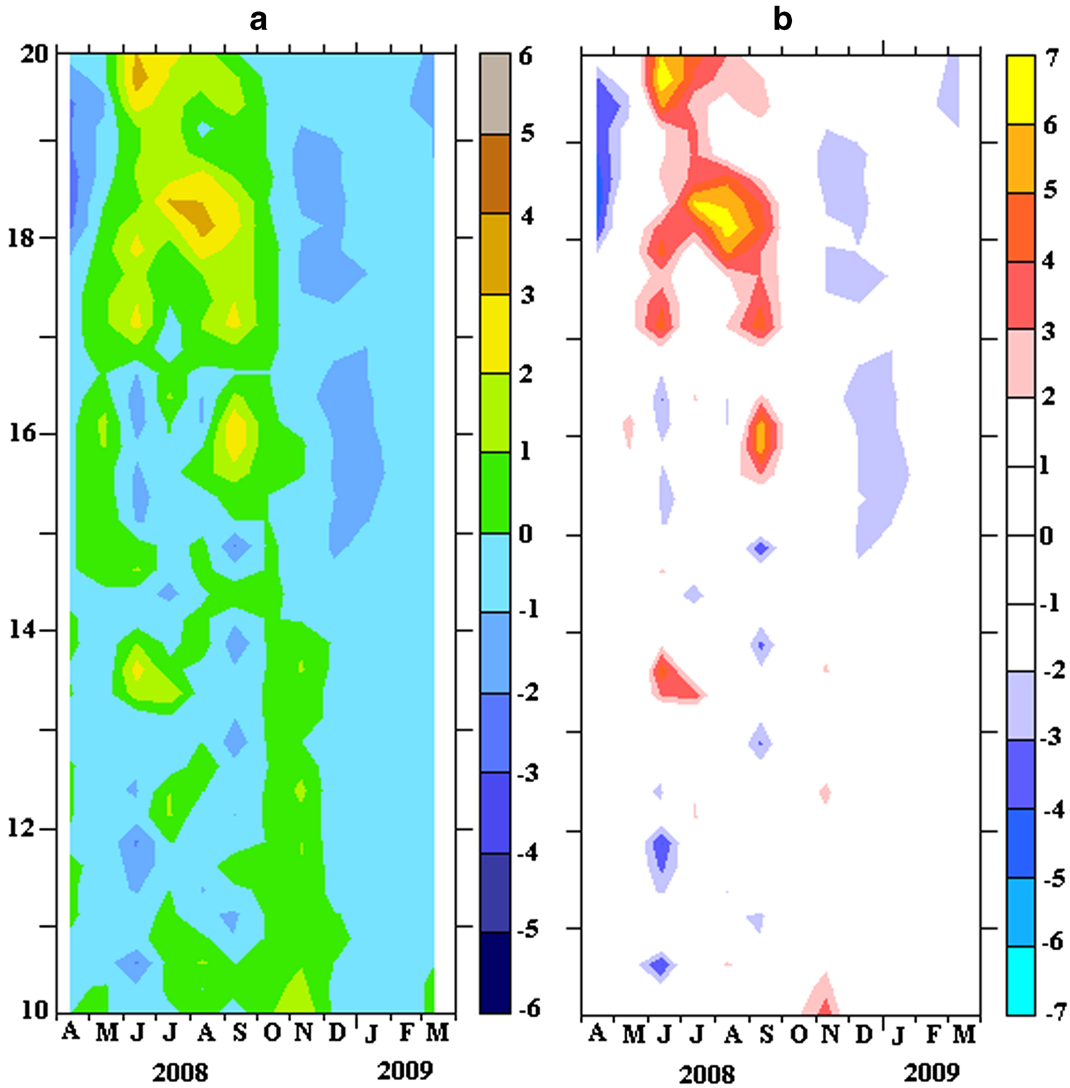

Fig. 7 Spatial distribution of **a** wind stress curl (×10^{-7}) and **b** Ekman pumping velocity (×10^{-3}) in the region (averaged between 86° E and 88° E)

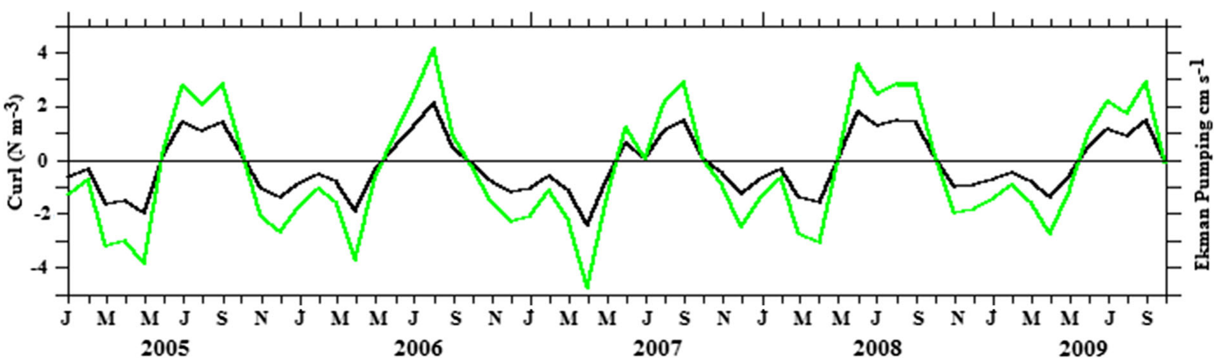

Fig. 8 Average wind stress curl and Ekman pumping in the NCE region (16–20° N and 86–88° E) from January to December during 2005–2009

Rossby waves (Potemra et al. 1991). Rao et al. (2010) reported the signatures of the upwelling Kelvin waves along the eastern and the northern rims of the BoB during August–September. Vinayachandran et al. (1996) also reported the occurrence of northward propagating Rossby waves in the BoB during August.

It is assumed that the baroclinic disturbance due to the passage of this wave may displace the pycnocline upward and results in the sustenance of the NCE. This indicates that the longer period of existence of the NCE is supported by multiple forcing mechanisms, subsequently acting one after another. Local wind stress curl and the resultant Ekman pumping is the primary important forcing during the summer (July–September) while during fall (October) and early phase of the winter (November and December) it was the westward propagating Rossby waves. Furthermore, the westward propagating signal clearly shows an amplification towards east of our study area (i.e. around 87° E). This may be speculated as due to the baroclinic supply of energy from the background state of the ocean. However, more analysis would be required to fully understand the complete mechanism of the origin and sustenance of the eddy.

Biological response to the NCE

NCE on phytoplankton

Analyses of Chl *a* indicate that NCE significantly influences the phytoplankton concentration of the region. The integrated nitrate, phosphate and silicate concentrations were considerably higher in the upper 120 m of NCE compared to other stations. The upsloping of nutrient-rich waters to upper layers (uplift of 40 to 50 m) in the NCE region was evident from isopleths of nutrients and DO, which were in accordance with the thermo-haline oscillation. The observed high surface (>0.2 mg m^{-3}) and column Chl *a* (25.7±3.6 mg m^{-2}, ~8 times higher than non-eddy location) in the NCE region signifies the response to nutrient enrichment in the euphotic zone. The high column Chl *a* in the NCE region supports the fact that subsurface increase is a general feature of the BoB. In accordance with the present study, other observations from the same region have shown that the enhancement of chlorophyll was more at the subsurface layers rather than at the surface (Prasanna Kumar et al. 2004, 2007, 2010). Nuncio and Prasanna Kumar (2012) in their study have attributed the stability of the water column to be the reason for the low surface values. They also suggested that when stratification is weak the mesoscale eddies are capable of upwelling the nutrients to the surface layers.

The proliferation of phytoplankton in response to nutrient enrichment results in increased Chl *a* concentration in the NCE region. Simultaneous enhancement of both small and large phytoplankton cells in response to nutrient enrichment is a common phenomenon. Chen (2000) observed both large and small phytoplankton cells in upwelling region in the southern East China Sea and suggested that relative abundance of these cells may vary with the source of nitrogen as well as the phase/age of the eddy. However, earlier studies from the region have reported that in general, diatoms formed the major component of the phytoplankton community (Madhu et al. 2006). Recent study from the southern BoB, reported that although smaller phytoplankton were dominant in the total Chl, the contribution of large phytoplankton was exceptionally high in the regions under the influence of SMC and associated eddies (Jyothibabu et al. 2015). In addition, the DCM, which was located between 60- and 80-m depth in the BoB, became shallow and more intense due to eddy pumping, resulting in high Chl *a* production (29.47 mg m^{-2}), particularly in the centre of the NCE than the peripheral regions (south 25.35 and north 22.25 mg m^{-2}).

In order to understand the impact of such long-lived eddies on phytoplankton concentration of the region, we analysed weekly averaged data of Chl *a* derived from MODIS. The satellite data showed high chlorophyll concentration (>0.35 mg m^{-3}) during the period from October to December. Due to extensive data gaps in the MODIS Chl *a*, especially over the northern BoB for a good part of the summer monsoon, analysis for these months could not be included. For this reason, several in situ data from earlier studies from this region were considered to get a clear picture of the Chl *a* concentration during the summer monsoon. It was found that Chl *a* concentration during the summer was approximately 0.28 mg m^{-3} (Madhupratap et al. 2003; Prasanna Kumar et al. 2010; Jyothibabu et al. 2008). Furthermore, monthly mean MODIS Chl *a* from 2004 to 2008 for the month of November showed high Chl *a* in the NCE region during all these years. The year-wise comparison of Chl *a* values for the 2004, 2005, 2006, 2007 and 2008 were 0. 26, 0.18, 0.23, 0.36 and 0.22 mg m^{-3}, respectively (av. 0.25 mg m^{-3}). The Chl *a* values for all these years were in agreement with the in situ observations which could explain the positive influence of NCE in the study region (Fig. 9).

NCE on mesozooplankton

Biovolume and composition The high mesozooplankton biovolume (0.35±0.36 ml m^{-3}) and numerical abundance (277±184 ind m^{-3}) observed in the mixed layer of the NCE region can be attributed to the high Chl *a*. Studies by Muraleedharan et al. (2007); Veronica (2008) in the cyclonic eddy region of Northern BoB also reported a positive response of the mesozooplankton to Chl *a*, similar to the present observation. However, these studies focused mainly on the copepod assemblages and zooplankton standing stock, whereas in the present study, variations in the composition of major zooplankton groups even within the NCE were a noticeable feature, and therefore, this provides the first report on the mesozooplankton community structure in the NCE.

The interesting feature observed was that the peripheral region of the NCE (20° N) sustained comparatively high mesozooplankton standing stock, in terms of biovolume (0.77 ml m^{-3}), abundance (472 ind m^{-3}) and number of groups (~17). The annual average of the mesozooplankton standing stock was reported to be 0.32 ml m^{-3} (Jyothibabu et al. 2008) and the increase in biovolume in this context was noticeably high in the peripheral region. This phenomenon could be attributed to the frontal characteristics of the edges that support the sustenance of planktonic standing stock (Franks 1992). Studies have explained that frontal regions have always been associated with high phytoplankton standing stock resulting from convergence and are favourable foraging area for predators. Attraction to food commonly accounts for the aggregation of organisms at or near the fronts and can also mechanically affect local concentration of organisms (Owen 1981).

Moreover, considering the geographical location of the study area and the amount of riverine discharge into the BoB, it can be reasonably assumed that alternative food sources, such as the detritus/organic matter, brought in by the rivers may also be supporting the sustenance of high biovolume of zooplankton standing stock in the northern periphery of the eddy. A study by Khodse et al. (2007) has also suggested that detritus is an alternative food source and could provide additional nutrition for mesozooplankton, particularly in the northern BoB, as some of the major

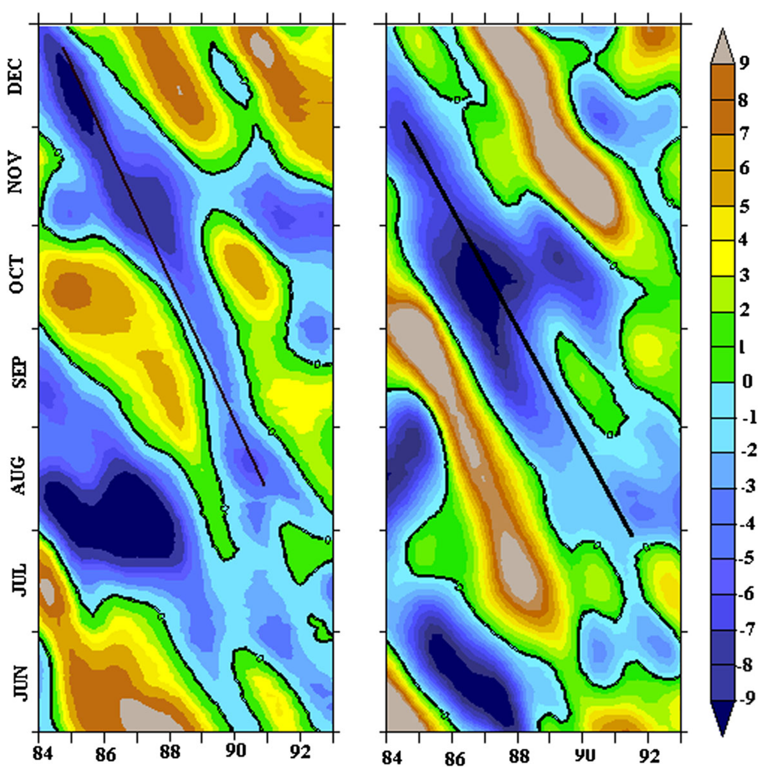

Fig. 9 Propagation of semi-annual Rossby waves along 17° N during the period **a** June–December 2008 and **b** during June–December 2009 (*black line* represents the propagation of low SSHA (x10^1 cm))

rivers such as Ganges, Brahmaputra, Godavari and Irawaddy discharge enormous volume of fresh water into this region (Fig. 10).

Added to this, the deepening of the mixed layer (47 and 31 m in the periphery and core, respectively) might have also supported the increase in the zooplankton stock in the northern periphery. All these factors combined seem to have enhanced the mesozooplankton standing stock by a factor of 4 in the periphery (0.77 ml m^{-3}) compared to the centre (0.19 ml m^{-3} at 18° 45′ N) and southern part of NCE (0.09 ml m^{-3} at 16° 45′ N). In addition, the long duration of eddies (~6 months), as evident in the present study, might also be an influential factor, leading to the increase in the mesozooplankton standing stock. As suggested by Huntley et al. 2000, the life span of eddies play an important role in the mesozooplankton distribution pattern. The reason is that the life cycle of most of the mesozooplankton community ranges approximately from weeks to months, and therefore, the persistence of NCE provides a favourable environment for their enhanced growth and reproduction. Therefore, the persistence of NCE in the region for approximately 6 months provided adequate time for zooplankton to grow and reproduce, resulting in an increase in the mesozooplankton standing stock. Consistent with the present observation, earlier studies have reported enhanced mesozooplankton standing stock from the eddy region in the BoB (Muraleedharan et al. 2007; Veronica 2008; Jyothibabu et al. 2008).

Copepoda, the most abundant group, also showed discernible variation in abundance between the centre and northern periphery (83 and 371 ind m^{-3}, respectively). Agreeing with the present study, in general and irrespective of seasons, Copepoda formed the predominant group in the mesozooplankton community (Achuthankutty et al. 1980). Besides Copepoda, the detritivores/omnivores such as Appendicularia and primary carnivores like Amphipoda were also abundant at the periphery. The gelatinous plankton-like medusae, Siphonophora and Salpa also contributed significantly to the mesozooplankton community in the northern peripheral region. The diverse assemblage of mesozooplankton groups at the edge of the doming region gives an indication that it is a foraging area for most of these groups and that had resulted in their aggregation. Such accumulation of mesozooplankton in the edges of eddies may be attributable to enhanced feeding and growth (Hernandez-Leon et al. 2001).

Studies have shown that mesoscale features are important in controlling the structure and productivity of marine planktonic communities (Owen 1981; Angel and Fasham 1983; Mann and Lazier 1991; Olson 1991). The changes observed in the zooplankton community structure and behaviour associated with longer duration of NCE, which provide ample time for zooplankton

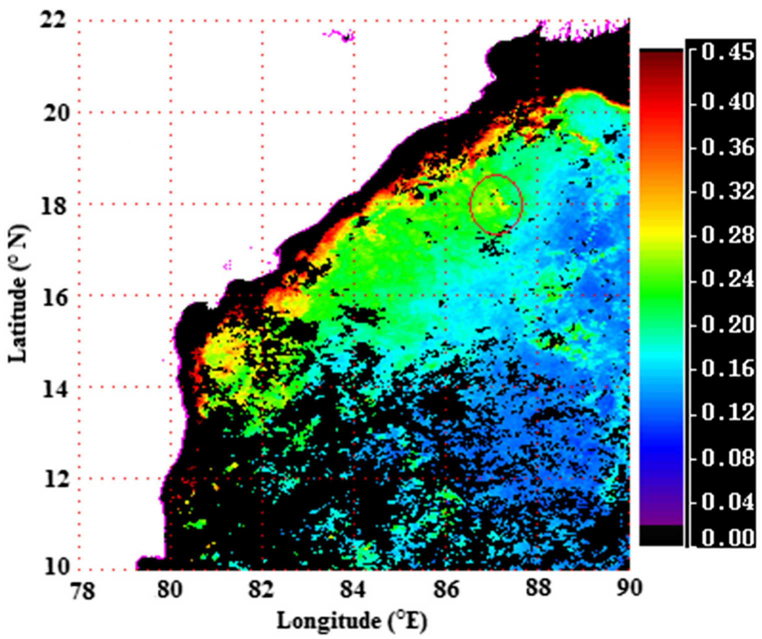

Fig. 10 Multi-year (2004–2008) monthly mean Chl *a* for the month of November. *Black circle* represents the NCE region

Table 2 Surface, column Chl *a* and mesozooplankton biomass in the northern BoB during different seasons

Author	Season	Position	Surface Chl *a* (mg m^{-3})	Column Chl *a* (mg m^{-2})	Mesozooplankton biomass (ml m^{-3})
Madhupratap et al. 2003	Summer	20° N and 88° E	0.26	11.5	–
Muraleedharan et al. 2007	Summer	17° 30′ N and 84° E	0.14	5.01	0.67
Jyothibabu et al. 2008	Summer	17–20.5° N	0.2 (average of Northern BoB)	13 (average of Northern BoB)	628 mg C m^{-2} (average of Northern BoB)
Veronica and Ramaiah 2009	Summer	20° N and 88° E	–	–	1200 mg C m^{-2} biomass reported higher than Muraleedharan et al. 2007
Prasanna Kumar et al. 2010	Summer	20° N and 88° E	0.28	11.1	–
Prasanna Kumar et al. 2007	Fall	20° N and 88° E	0.13	11.3	–
Jyothibabu et al. 2008	Winter	17–20.5° N	0.09 (average of Northern BoB)	9.42 (average of Northern BoB)	776 mg C m^{-2} (average of Northern BoB)
Prasanna Kumar et al. 2010	Winter	20° N and 88° E	0.13	22.2	–
Present study	Winter	20° N and 87° E	0.2	22.3	0.71

population to grow and reproduce could have important implications on the trophic levels and functioning of food webs. The feeding behaviour and availability of preferential food would favour increase in abundance of certain groups and simultaneous increase in transport of organic matter. Moreover, the generation time of zooplankton, especially that of Copepoda, which forms the major component of mesozooplankton community, is approximately 3 weeks, and therefore, the longer existence of the NCE could provide adequate time for such groups to exhibit reproductive response (Angel and Fasham 1983; Huntley et al. 2000).

The impact of the NCE on the biological production in the present study and the positive impact of cyclonic eddy during summer (chlorophyll and zooplankton) and fall inter-monsoon and winter monsoon (primary) reported from the same region are given Table 2. Furthermore, on considering the period of existence of the NCE, the study implies that it can help in sustaining high biological production for a longer period in an oligotrophic region like the BoB. The positive effects of such mesoscale processes suggest that the formation of the NCE and its prolonged existence from summer to winter (July–December) could initiate significant biological pulses in the region, linking physical processes and plankton production. Thus, the eddy prominence (short and long lived) significantly influences the biological pump, thereby mediating the efficient transfer of carbon from lower to higher trophic levels within a short span of time. Even though there are reasonable evidences supporting the proposed hypothesis, further studies based on time series data and modelling efforts would provide more insights on the biogeochemistry of the region where the production is governed by episodic events.

Conclusion

The presence of a cyclonic eddy (NCE) in the northern BoB and its chemical and biological responses during the early phase of winter monsoon are discussed. The enhanced level of nutrients in the euphotic column due to eddy pumping resulted in eight fold increase in Chl *a*, and this led to high mesozooplankton standing stock. The variation in the mesozooplankton community structure to the mesoscale process was evident, suggesting that these organisms respond rapidly to the environmental changes. The persistent and longer duration

(~6 months) of the NCE significantly influences the biological production of the BoB from summer to winter. Local wind stress curl and the resultant Ekman pumping have been identified as the important forcing mechanism for the formation of NCE during summer (July–September). During fall and the start of winter, its existence is being maintained by the westward propagating semi-annual Rossby waves. The longer existence of the NCE provided adequate time for zooplankton to exhibit reproductive response, which resulted in noticeable increase in secondary standing stock. The enhanced biological production (primary and secondary) suggests that the existence of NCE from summer to early winter (July–December) could initiate significant biological pulses in the region. These complex dynamics of NCE undoubtedly influences the ecological structure of the generally oligotrophic BoB making it locally biologically *'active'*.

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References

Achuthankutty, C. T., Madhupratap, M., Nair, V. R., Nair, S. R. S., & Rao, T. S. S. (1980). Zooplankton biomass and composition in the western Bay of Bengal during southwest monsoon. *Indian Journal of Marine Sciences, 9*, 201–206.

Allen, C. B., Kanda, J., & Laws, E. A. (1996). New production and photo-synthetic rates within and outside a cyclonic mesoscale eddy in the North Pacific subtropical gyre. *Deep-Sea Research Part I, 43*, 917–936.

Angel, M. V., & Fasham, M. J. R. (1983). Eddies and biological processes. In A. Robinson (Ed.), *Eddies in marine science* (pp. 492–524). New York: Springer.

Aristegui, J., Tett, P., Hernandez-Guerra, A., Basterretxea, G., Montero, M. F., Wild, K., Sangra, P., Hernandez-Leon, S., Canton, M., & Garcia-Braun, J. A. (1997). The influence of island-generated eddies on chlorophyll distribution: a study of mesoscale variation around Gran Canaria. *Deep-Sea Research Part I, 44*, 71.

Babu, M. T., Prasannakumar, S., & Rao, D. P. (1991). A subsurface cyclonic eddy in the Bay of Bengal. *Journal of Marine Research, 49*, 403–410.

Babu, M. T., Sarma, Y. V. B., Murty, V. S. N., & Vethamony, P. (2003). On the circulation in the Bay of Bengal during northern spring inter-monsoon (March-April 1987). *Deep-Sea Research Part II, 50*(5), 855–865.

Barth, J. A., Cowles, T. J., & Pierce, S. D. (2001). Mesoscale physical and bio-optical structure of the Antarctic Polar Front near 170 degrees W during austral spring. *Journal of Geophysical Research, 106*(C7), 13879–13902.

Chen, Y.-L. L. (2000). Comparisons of primary productivity and phytoplankton size structure in the marginal regions of southern East China Sea. *Continental Shelf Research, 20*, 437–458.

Falkowski, P. G., Ziemann, D., Kolber, Z., & Bienfang, P. K. (1991). Role of eddy pumping in enhancing primary production in the ocean. *Nature, 352*, 55–58.

Franks, P. J. S. (1992). Sink or swim: accumulation of biomass at fronts. *Marine Ecology Progressive Series, 82*, 1–12.

Garcia, C. A. E., Sarma, Y. V. B., Mata, M. M., & Garcia, V. M. T. (2004). Chlorophyll variability and eddies in the Brazil-Malvinas Confluence region. *Deep-Sea Research Part II, 51*, 159–172.

Gill, A. E. (1982). *Atmosphere-ocean dynamics* (p. 662). New York: Academic.

Gomes, H., Goes, J. I., & Saino, T. (2000). Influence of physical processes and freshwater discharge on the seasonality of phytoplankton regime in the Bay of Bengal. *Continental Shelf Research, 20*, 313–330.

Grasshoff, K., Ehrhardt, M., & Krembling, K. (1983). In K. Grasshoff, M. Ehrhardt, & K. Kremling (Eds.), *Methods of seawater analysis* (pp. 89–224). Weinheim: Verlag Chemie.

Hernandez-Leon, S., Almeida, C., Gómez, M., Torres, S., Montero, I., & Portillo-Hahnefeld, A. (2001). Zooplankton biomass and indices of feeding and metabolism in island generated eddies around Gran Canaria. *Journal of Marine Systems, 30*, 51–66.

Huntley, M. E., Gonzales, A., Zhu, Y., & Irogoien, X. (2000). Zooplankton dynamics in a mesoscale eddy-jet system off California. 201. *Marine Ecology Progress Series, 201*, 165–178.

Jury, R. M., & Huang, B. (2004). The Rossby wave as a key mechanism of Indian Ocean climate variability. *Deep Sea Research, Part I, 51*, 2123–2136. doi:10.1016/j.dsr.2004.06.005.

Jyothibabu, R., Maheswaran, P. A., Madhu, N. V., Mohammed, A. T. T., Vijay, J. G., Haridas, P. C., Venugopal, P., Revichandran, C., Nair, K. K. C., & Gopalakrishnan, T. C. (2004). Differential response of winter cooling on biological production in the northeastern Arabian Sea and northwestern Bay of Bengal. *Current Science, 87*, 783–791.

Jyothibabu, R., Madhu, N. V., Maheswaran, P. A., Jayalakshmy, K. V., Nair, K. K. C., & Achuthankutty, C. T. (2008). Seasonal variation of microzooplankton (20-200 m) and its possible implications on the vertical carbon flux in the western Bay of Bengal. *Continental Shelf Research, 28*(6), 737–755.

Jyothibabu, R., Vinayachandran, P. N., Madhu, N. V., Robin, R. S., Karnan, C., Jagadeesan, L., & Anjusha, A. (2015). Phytoplankton size structure in the southern Bay of Bengal modified by the Summer Monsoon Current and associated eddies: implications on the vertical biogenic flux. *Journal of Marine Systems, 143*, 98–119.

Khodse, V. B., Fernandes, L., Gopalkrishna, V. V., Bhosle, N. B., Fernandes, V., Matondkar, S. G. P., & Bhushan, R. (2007). Distribution and seasonal variation of concentrations of particulate carbohydrates and uronic acids in the northern Indian Ocean. *Marine Chemistry, 103*, 327–346.

Kurien, P., Ikeda, M., & Valsala, V. K. (2010). Mesoscale variability along the east coast of India in spring as revealed from satellite and OGCM simulations. *Journal of Oceanography, 66*, 273–289.

Legeckis, R. (1987). Satellite observation of a western boundary current in the Bay of Bengal. *Journal of Geophysical Research, 92C*, 12974–12978.

Letelier, R. M., Karl, D. M., Abbott, M. R., Flament, P., Freilich, M., Lukas, R., & Strub, T. (2000). Role of late winter mesoscale events in the bio-geochemical variability of the upper water column of the North Pacific Subtropical Gyre. *Journal of Geophysical Research, 105*(C12), 28723–28739.

Madhu, N. V., Maheswaran, P. A., Jyothibabu, R., Sunil, V., Revichandran, C., Balasubramanian, T., Gopalakrishnan, T. C., & Nair, K. K. C. (2002). Enhanced biological production off Chennai triggered by October 1999 super cyclone (Orissa). *Current Science, 82*, 1472–1479.

Madhu, N. V., Jyothibabu, R., Maheswaran, P. A., Gerson, V. J., Gopalakrishnan, T. C., & Nair, K. K. C. (2006). Lack of seasonality in phytoplankton standing stock (chlorophyll a) and production in the western Bay of Bengal. *Continental Shelf Research*. doi:10.1016/j-csr.2006.06.004.

Madhupratap, M., Gauns, M., Ramaiah, N., Prasanna Kumar, S., Muraleedharan, P. M., DeSousa, S. N., Sardessai, S., & Muraleedharan, U. D. (2003). Biogeochemistry of the Bay of Bengal: physical, chemical and primary productivity characteristics of the central and western Bay of Bengal during summer monsoon 2001. *Deep-Sea Research Part II, 50*(5), 881–896.

Madhusoodhanan, P., & James, V. V. (2003). Thermohaline features of the subsurface cyclonic eddy in the south central Bay of Bengal during August 1999. *Proceedings of the Indian Academy of Sciences (Earth and Planetary Sciences), 112*, 233–237.

Maneesha, K., Sarma, V. V. S. S., Reddy, N. P. C., Sadhuram, Y., Ramana Murty, T. V., Sarma, V. V., & Kumar, M. D. (2011). Meso-scale atmospheric events promote phytoplankton blooms in the coastal Bay of Bengal. *Journal of Earth System Science, 120*, 1–10.

Mann, K. H., & Lazier, J. R. N. (1991). *Dynamics of marine ecosystems: biological-physical interactions in the oceans*. Oxford: Blackwell Scientific Publication.

McCreary, J. P., Kundu, P. K., & Molinari, R. L. (1993). A numerical investigation of the dynamics, thermodynamics and mixed layer processes in the Indian Ocean. *Progress in Oceanography, 31*, 181–244.

McGillicuddy, D. J., Robinson, A. R., Siegel, D. A., Jannasch, H. W., Johnson, R., Dickey, T. D., McNeil, J., Michaels, A. F., & Knap, A. H. (1998). Influence of mesoscale eddies on new production in the Sargasso Sea. *Nature, 394*, 263–266.

McNeil, J. D., Jannasch, H. W., Dickey, T., McGillicuddy, D., Brze-zinski, M., & Sakamoto, C. M. (1999). New chemical, bio-optical and physical observations of upper ocean response to the passage of a mesoscale eddy off Bermuda. *Journal of Geophysical Research, 104*(C7), 15537–15548.

Moran, X. A. G., Taupier-Letage, I., Vazquez-Dominguez, E., Ruiz, S., Arin, L., Raimbault, P., & Estrada, M. (2001). Physical-biological coupling in the Algerian Basin (SW Mediterranean): influence of mesoscale instabilities on the biomass and production of phytoplankton and bacterioplankton. *Deep Sea Research, Part I, 48*, 405.

Morel, A., & Berthon, J. F. (1989). Surface pigments, algal biomass profiles, and potential production of the euphotic layer: relationships reinvestigated in view of remote-sensing applications. *Limnology and Oceanography, 34*, 1545–1562.

Muraleedharan, K. R., Jasmine, P., Achuthankutty, C. T., Revichandran, C., Dinesh Kumar, P. K., Anand, P., & Rejomon, G. (2007). Influence of basin-scale and mesoscale physical processes on biological productivity in the Bay of Bengal during the summer monsoon. *Progress in Oceanography, 72*(4), 364–383.

Murty, V. S. N., Suryanarayana, A., & Rao, D. P. (1993). Current structure and volume transport across 12°N in the Bay of Bengal. *Indian Journal of Marine Sciences, 22*, 12–16.

Murty, V. S. N., Gupta, G. V. M., Sarma, V. V., Rao, B. P., Jyothi, D., Shastri, P. N. M., & Supraveena, Y. (2000). Effect of vertical stability and circulation on the depth of the chlorophyll maximum in the Bay of Bengal during May-June 1996. *Deep Sea Research, Part I, 47*, 859–873.

Nuncio, M. (2007). Role of eddies in the Bay of Bengal circulation and hydrography and in the distribution of nutrients and chlorophyll. PhD thesis, Goa University.

Nuncio, M. S., & Prasanna Kumar, S. (2012). Life cycle of eddies along western boundary of the Bay of Bengal and their implications. *Journal of Marine Systems, 94*, 9–17.

Olson, D. B. (1991). Rings in the ocean. *Annual Review of Earth and Planetary Science, 19*, 283–311.

Owen, R. W. (1981). Fronts and eddies in the sea: mechanisms, interactions, and biological effects. In A. R. Longhurst (Ed.), *analysis of marine ecosystems* (pp. 197–233). New York: Academic.

Potemra, J. T., Luther, M. E., & O'Brien, J. J. (1991). The seasonal circulation of the upper ocean in the Bay of Bengal. *Journal of Geophysical Research, 96*, 12,667–12,683.

Prasad, T. G. (1997). Annual and seasonal mean buoyancy fluxes for the tropical Indian Ocean. *Current Science, 73*, 667–674.

Prasanna Kumar, S., Muraleedharan, P.M., Prasad, T.G., Gauns, M., Ramaiah, N., de Souza, S.N., Sideway, S. & Madhupratap, M. (2002). Why is the Bay of Bengal less productive during summer monsoon compared to the Arabian Sea? *Geophysical Research Letters, 29*, doi:10.1029/2002GL016013.

Prasanna Kumar, S., Nuncio, M., Narvekar, Ajoykumar, J., Sardesai, S., Desouza, S. N., Gauns, M., Ramaiah, N., & Madhupratap, M. (2004). Are eddies nature's trigger to enhance biological productivity in the Bay of Bengal? *Geophysical Research Letters, 31*, L07309. doi:10.1029/2003GL01927.

Prasanna Kumar, S., Nuncio, M., Ramaiah, N., Sardessai, S., Narvekar, J., Fernandes, V., & Paul, J. T. (2007). Eddy-mediated biological productivity in the Bay of Bengal during fall and spring intermonsoons. *Deep Sea Research, Part I, 54*, 619–1640.

Prasanna Kumar, S., Nuncio, M., Narvekar, J., Ramaiah, N., Sardessai, S., Gauns, M., Fernandes, V., Paul, J. T., Jyothibabu, R., & Jayaraj, K. J. (2010). Seasonal cycle of physical forcing and biological response in the Bay of Bengal. *Indian Journal of Marine Sciences, 39*(3), 388–405.

Qasim, S. Z. (1977). Biological productivity of the Indian Ocean. *Indian Journal Marine Sciences, 6*, 122–137.

Radhakrishna, K., Bhattathiri, P. M. A., & Devassy, V. P. (1978). Primary productivity of Bay of Bengal during August-September, 1976. *Indian Journal of Marine Sciences, 7*, 94–98.

Ramasastry, A. A., & Balaramamurty, C. (1957). Thermal fields and oceanic circulation along the east coast of India. *Proceedings Indian Academy Sciences, 46*, 293–323.

Rao, D.P. & Sastry, J.S. (1981). Circulation and distribution of some hydrographical properties during the late winter in the Bay of Bengal. Mahasagar, 14, no 1.

Rao, R. R., & Sivakumar, R. (2003). Seasonal variability of sea surface salinity and salt budget of the mixed layer of the north Indian Ocean. *Journal of Geophysical Research, 108*(C1), 3009. doi:10.1029/2001JC000907.

Rao, R. R., Girishkumar, M. S., Revichandran, M., Rao, A. R., Gopalakrishna, V. V., & Thadathil, P. (2010). Interannual variability of Kelvin wave propagation in the wave guides of the equatorial Indian Ocean, the coastal Bay of Bengal, and the southeastern Arabian Sea during 1993–2006. *Deep Sea Research, Part I, 57*, 1–13. doi:10.1016/j.dsr.2009.10.008.

Robinson, A. R., McGillicuddy, D. J., Calman, J., Ducklow, H. W., Fasham, M. J. R., Hoge, F. E., Leslie, W. G., McCarthy, J. J., Podewski, S., Porter, D. L., Saure, G., & Yoder, J. A. (1993). Mesoscale and upper ocean variabilities during the 1989 JGOFS bloom study. *Deep Sea Research, Part II, 40*, 9–35.

Sabu, P., & Revichandran, C. (2011). Mixed layer processes of Arabian Sea Warm Pool during spring intermonsoon: a study based on observational and satellite data. *International Journal of Remote Sensing, 32*(19), 5425–5441.

Sanilkumar, K. V., Kuruvilla, T. V., Jogendranath, D., & Rao, R. R. (1997). Observation of the western boundary current of the Bay of Bengal. *Deep Sea Research, Part I, 44*, 135–145.

Senguptha, R., De Sousa, S. N., & Joseph, T. (1977). On nitrogen and phosphorous in the western Bay of Bengal. *Indian Journal of Marine Sciences, 6*, 107–110.

Shetye, S. R., Gouveia, A. D., Shenoi, S. S. C., Sundar, D., Michael, G. S., & Nampoothiri, G. (1993). The western boundary current of the seasonal subtropical gyre in the Bay of Bengal. *Journal of Geophysical Research, 98*, 945–954.

Shetye, S. R., Gouveia, A. D., Shankar, D., Shenoi, S. S. C., Vinayachandran, P. N., Sundar, D., Michael, G. S., & Nampoothiri, G. (1996). Hydrography and circulation in the western Bay of Bengal during the northeast monsoon. *Journal of Geophysical Research, 101*, 14,011–14,025.

Strickland, J. D. H., & Parsons, T. R. (1972). A practical handbook of seawater analysis, II ed. *Bulletin-Fisheries Research Board of Canada, 167*, 310.

Subramanian, V. (1993). Sediment load of Indian rivers. *Current Science, 64*, 928–930.

UNESCO (1988). River inputs to ocean systems: status and recommendations for research. UNESCO Technical Papers in Marine Science, No.55. *Final report of SCOR Working Group, 46*, Paris, p.25.

Veronica, F. (2008). The effect of semi-permanent eddies on the distribution of mesozooplankton in the central Bay of Bengal. *Journal of Marine Research, 66*, 465–488.

Veronica, F., & Ramaiah, N. (2009). Mesozooplankton community in the Bay of Bengal (India): spatial variability during the summer monsoon. *Aquatic Ecology, 43*(4), 951–963.

Vinayachandran, P. N., & Mathew, S. (2003). Phytoplankton bloom in the Bay of Bengal during winter monsoon and its intensification by cyclones. *Geophysical Research Letters, 30*(11), 1572.

Vinayachandran, P. N., Shetye, S. R., Sengupta, D., & Gadgil, S. (1996). Forcing mechanisms of the BoB circulation. *Current Science, 71*(10), 753–763.

Yu, L., O'Brien, & Yang, J. (1991). On the remote forcing of the circulation in the Bay of Bengal. *Journal of Geophysical Research, 96*, 20,449–20,454.